Introduction

The goal of the ZEMAX analysis of the Curtis-Schmidt optical system is to determine if a field flattener will produce PreCam images that have uniform focus across the entire focal plane, rather than having a focus that varies across the focal plane due to the intrinsic curvature of the field. Secondarily, the optimal optical properties of the field flattener (specifically, the radius of curvature of the front and back surfaces of the FF/ dewar window) must be determined. As an important check on the accuracy of ZEMAX, we also attempt to recreate the observed results of PreCam under different focusing conditions. This ZEMAX analysis compared three different scenarios: i) without a field flattener and with the best focus at the center of the image; ii) without a field flattener and with the best focus partway between the center and the edge, thus giving the largest possible area with good focus; and iii) with a field flattener, thus giving uniform focus across the entire plane. See also the Curtis Schmidt Optical Elements and Ray-Tracing figure below.

The Data

From the spot size determinations, shown in the figures below, for case i) we see the RMS (Geometric) spot size increases monotonically from 5 (20) microns to 50 (100) microns, based on the (angular) distance from the center of the plane (up to 1.25 degrees/about 45 mm). For case ii) we see the RMS (Geometric) spot size varies from 27 (50) microns down to 8 (25) microns and then back to 25 (61) microns. For case iii), the RMS (Geometric) spot size varies between 5 (16) microns and 8 (30) microns.
For reference, observed spot sizes from PreCam data tend to vary from 30 microns (2 pixels) to 120 microns (8 pixels) across the highly curved focal plane, with some additional variation due to non-optimal focusing in certain cases.

While the field flattener obviously improves the focus in this idealized situation, we must also determine the degradation from ideal of the “as-built” system by calculating the effect of Tolerancing. This calculation is performed in two ways:
a) The sensitivity analysis considers the effects on system performance for each tolerance individually, then the aggregate performance is estimated by a root-sum-square calculation.
b) The Monte Carlo method estimates the aggregate effects of all tolerances by generating a series of random lenses which meets the specified tolerances, then evaluates the criterion.
The default Tolerances for each optical component were used for both methods and applied to all 3 cases, as shown in the output below. The resultant spot size is given as only one number (not a series of numbers corresponding to all angular positions), but the effect on each position can be inferred from the overall change.
For case i), method a) shows a spot size degradation from 32 microns (nominal) to 51 microns (expected)--an increase of 56%. Method b) shows a spot size degradation from 32 microns to 35 microns (Best Case simulation) or 49 Microns (Worst Case), with a mean of 41 microns--an increase of 28%. As noted above, however, a single value for the spot size does not reflect the variation as a function of focal plane position--while the center of the focal plane may be significantly better, the edges will certainly be much worse.

For case ii), method a) shows a spot size degradation from 48 microns (nominal) to 63 microns (expected)--an increase of 31%. Method b) shows a spot size change from 48 microns to 40 microns (Best Case simulation) or 57 Microns (Worst Case), with a mean of 50 microns--an increase of 4%. This case is clearly the least sensitive to “as-built” tolerances, though as with case i), the variation in spot size as a function of angle is not fully captured by the single output value--we can expect observed results both better and worse than these numbers, depending on focal plane position.
For case iii), method a) shows a spot size degradation from 7 microns (nominal) to 58 microns (expected)--an increase of over 600%. Method b) shows a spot size degradation from 7 microns to 17 microns (Best Case simulation) or 52 Microns (Worst Case), with a mean of 28 microns--an increase of 300%. Clearly this case is the most sensitive to “as-built” tolerances, but also the least sensitive to angular position--unlike cases i) and ii), very little variation in spot size is expected across the focal plane, thus these quantitative results can be understood in a much more straightforward fashion. It is also worth noting that the “Worst Offenders” contributing to the degradation of focus this case are the (X,Y) tilt of the primary and secondary mirrors--these degrade the spot size by as much as 31 and 13 microns, respectively. If the tolerances on these tilts can be reduced by even a factor of 2, the performances improves dramatically, in the worst case degrading the spot by only about 12 microns (not shown).

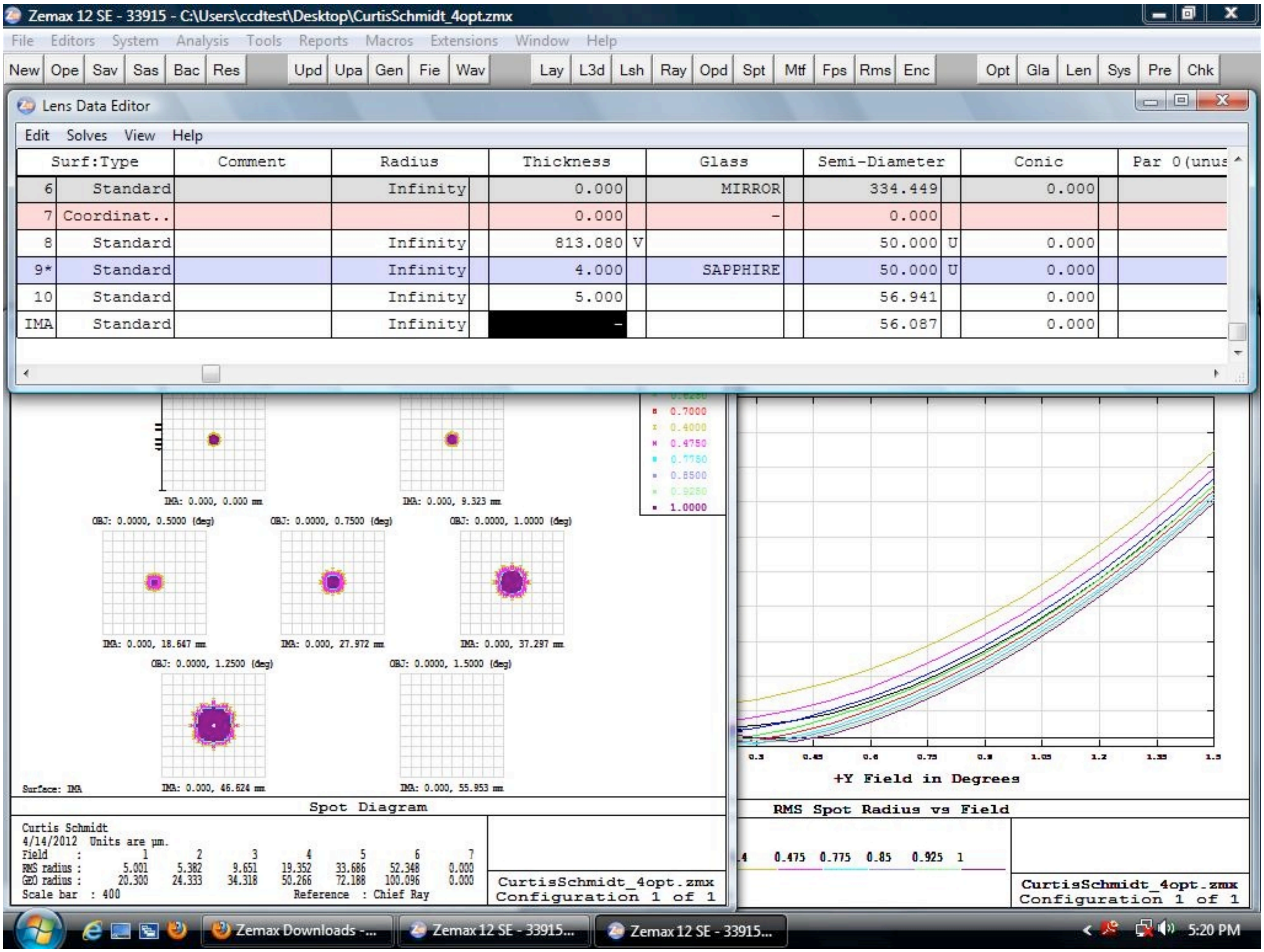
Conclusions

First, the data show that we can recreate the spot sizes observed with PreCam on the Curtis Schmidt in cases i) & ii). While the raw data show RMS spot sizes slightly smaller than observed, the Geometric spot sizes correspond more closely to the realistic spot sizes. Furthermore, the effect of the “as-built” Tolerances--in particular, the trend of increasing the spot size by several tens of percent--reinforces the accuracy of these more realistic results. We conclude that the ZEMAX analysis successfully recreates the observed PreCam results, and that the performance without a field flattener is not adequate given our desired performance.

Finally, despite the large percentage increase in the spot size when the tolerances are factored into case iii), we see that the expected spot size is still between 2 and 4 pixels, even in the worst case simulation. Thus, unless the “as-bulit” tolerances are egregiously worse than those incorporated into these ZEMAX calculations, the field flattener <u>will</u> perform as required to provide substantially smaller and more uniform spot sizes across the focal plane. And if the “as-built” tolerances are better than assumed, especially for the X and Y tilt of the primary and secondary mirror, then the field flattener is likely to perform even better than has been quantified here.

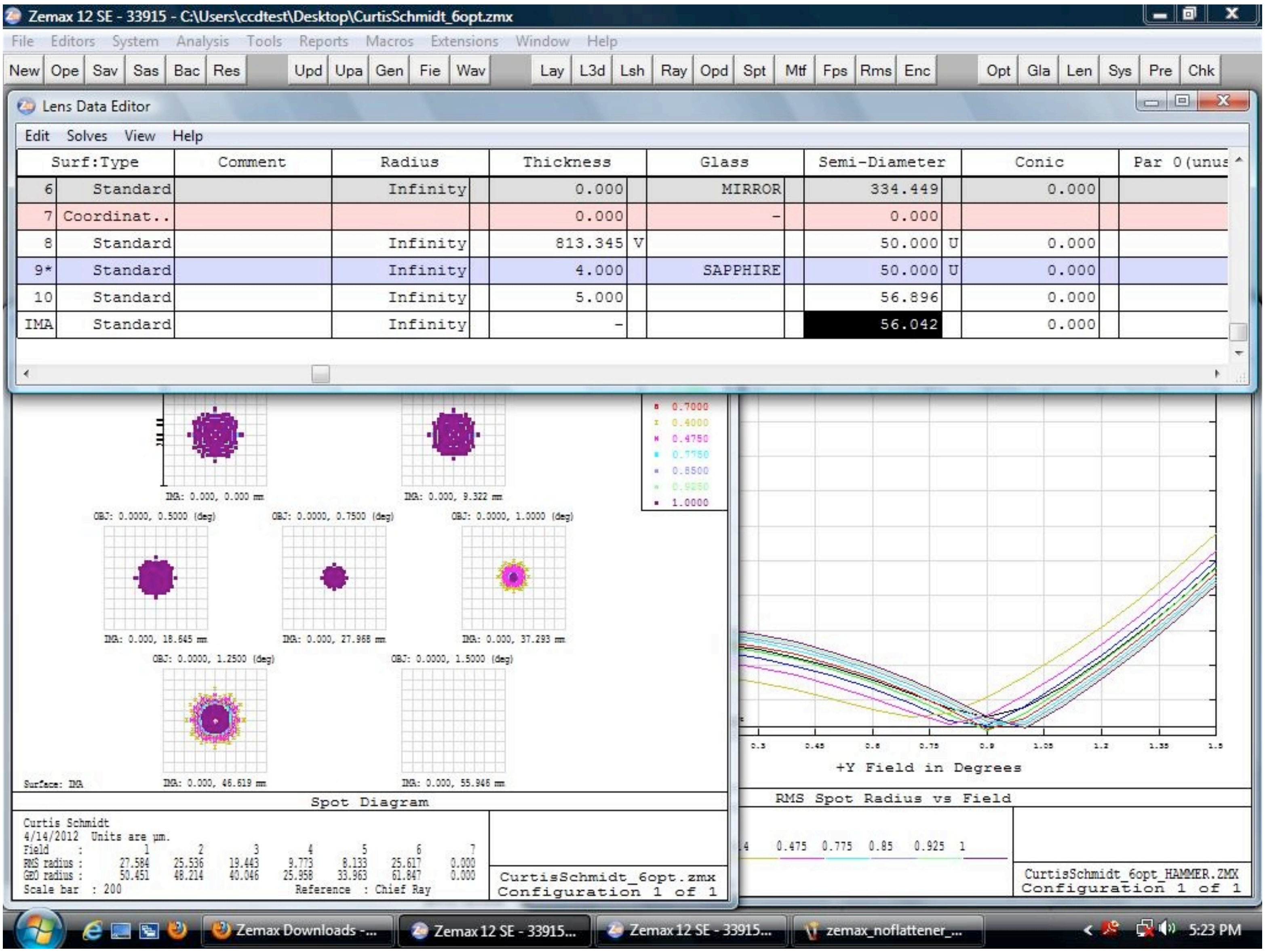
Spot Size--case i)

The lower left figure in this screen capture of ZEMAX output shows the spot size as a function of angular position from the center of the focal plane, in quarter degree increments from 0.0 to 1.25 degrees (the rays at 1.50 degrees are vignetted by the C-S and PreCam optics, and thus are not included in this analysis.)

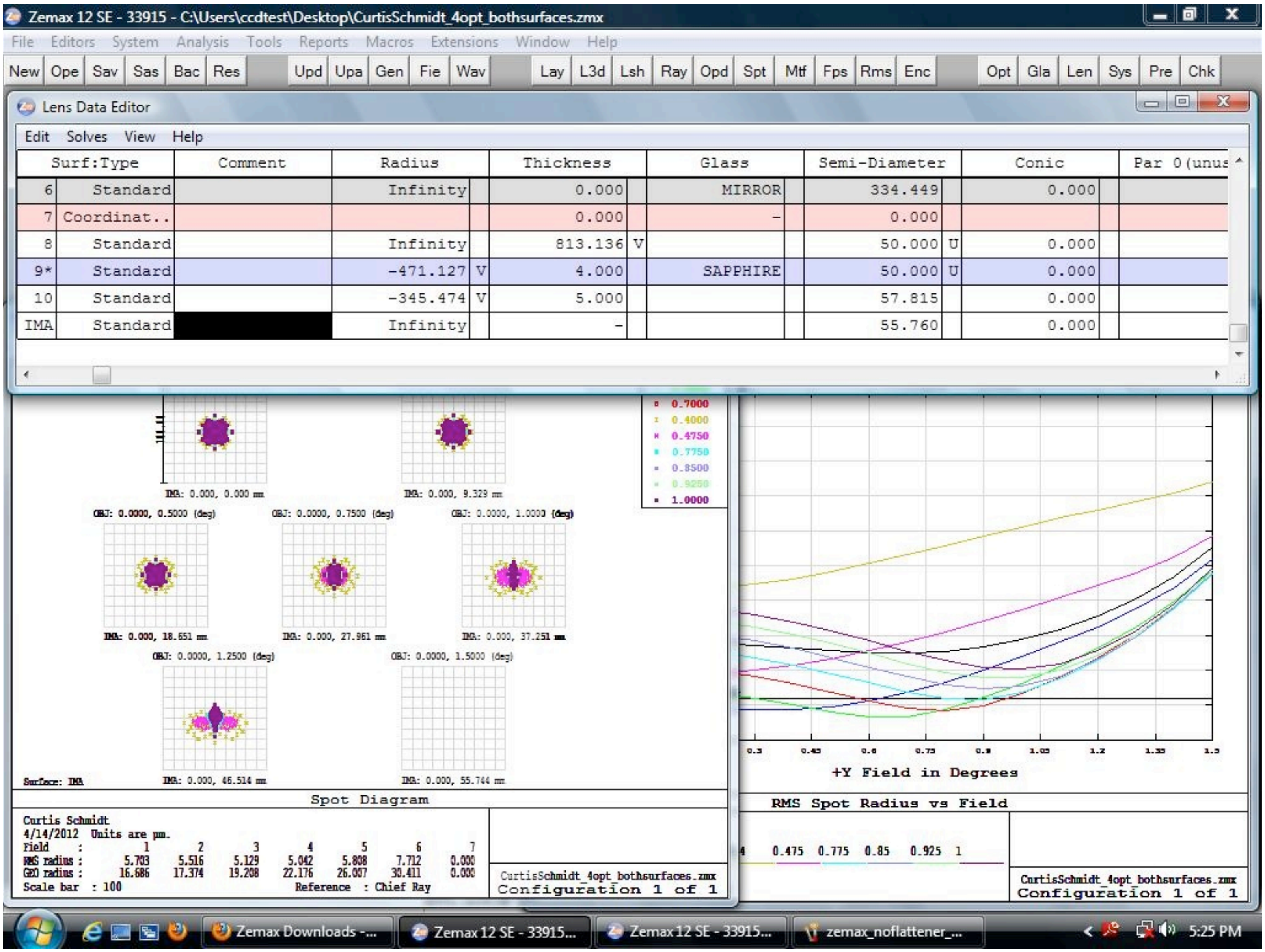


Zemax and the Curtis-Schmidt

Spot Size--case ii)



Spot Size--case iii)



Analysis of Tolerances (i)
File : C:\Users\ccdtest\Desktop\CurtisSchmidt_6opt.zmx
Title: Curtis Schmidt

Date : 4/20/2012
Units are Millimeters.
All changes are computed using linear differences.
Paraxial Focus compensation only.
WARNING: Boundary constraints on compensators will be ignored.
Criterion : RMS Spot Radius in Millimeters
Mode : Sensitivities
Sampling : 2
Nominal Criterion : 0.03265992
Test Wavelength : 0.6328

Sensitivity Analysis:
Worst offenders:

Type			Value	Criterion	Change
TETX	4	4	-0.20000000	0.04438369	0.01172377
TETY	4	4	0.20000000	0.04438369	0.01172377
TETX	4	4	0.20000000	0.04438369	0.01172377
TETY	4	4	-0.20000000	0.04438369	0.01172377
TTHI	5	6	-0.20000000	0.03816702	0.00550709
TETX	6	6	-0.20000000	0.03769493	0.00503501
TETX	6	6	0.20000000	0.03769493	0.00503501
TETY	6	6	0.20000000	0.03525288	0.00259296
TETY	6	6	-0.20000000	0.03525288	0.00259296
TTHI	6	7	0.20000000	0.03501846	0.00235854

Estimated Performance Changes based upon Root-Sum-Square method:
Nominal RMS Spot Radius : 0.03265992
Estimated change : 0.01822395
Estimated RMS Spot Radius : 0.05088387
Compensator Statistics:
Change in back focus:
Minimum : -0.400000
Maximum : 0.400000
Mean : -0.000000
Standard Deviation : 0.062905

Monte Carlo Analysis:
Number of trials: 20
Initial Statistics: Normal Distribution

Trial	Criterion	Change
1	0.04552281	0.01286289
2	0.04748389	0.01482397

3	0.03763048	0.00497055
4	0.04313087	0.01047095
5	0.04717560	0.01451568
6	0.04878436	0.01612443
7	0.03726984	0.00460991
8	0.03636897	0.00370905
9	0.03735216	0.00469224
10	0.04481734	0.01215741
11	0.04125732	0.00859740
12	0.03578731	0.00312738
13	0.04082153	0.00816160
14	0.03989068	0.00723076
15	0.04126913	0.00860920
16	0.03656577	0.00390585
17	0.03688130	0.00422138
18	0.04098716	0.00832724
19	0.03950894	0.00684902
20	0.03487874	0.00221881

Number of traceable Monte Carlo files generated: 20
Nominal 0.03265992
Best 0.03487874 Trial 20
Worst 0.04878436 Trial 6
Mean 0.04066921
Std Dev 0.00414167

90% > 0.04732975
80% > 0.04517008
50% > 0.04035610
20% > 0.03672353
10% > 0.03607814

End of Run.

Analysis of Tolerances (ii)
File : C:\Users\ccdtest\Desktop\CurtisSchmidt_4opt.zmx
Title: Curtis Schmidt

Date : 4/20/2012
Units are Millimeters.
All changes are computed using linear differences.
Paraxial Focus compensation only.
WARNING: Boundary constraints on compensators will be ignored.
Criterion : RMS Spot Radius in Millimeters
Mode : Sensitivities
Sampling : 2
Nominal Criterion : 0.04847883
Test Wavelength : 0.6328

Sensitivity Analysis:
Worst offenders:

Type			Value	Criterion	Change
TTHI	5	6	-0.20000000	0.05813719	0.00965836
TETX	4	4	-0.20000000	0.05447075	0.00599192
TETY	4	4	0.20000000	0.05447075	0.00599192
TETY	4	4	-0.20000000	0.05447075	0.00599192
TETX	4	4	0.20000000	0.05447075	0.00599192
TTHI	6	7	0.20000000	0.05319457	0.00471574
TTHI	4	5	0.20000000	0.05319457	0.00471574
TETX	6	6	-0.20000000	0.05095121	0.00247238
TETX	6	6	0.20000000	0.05095121	0.00247238
TETY	6	6	0.20000000	0.04972011	0.00124128

Estimated Performance Changes based upon Root-Sum-Square method:
Nominal RMS Spot Radius : 0.04847883
Estimated change : 0.01428818
Estimated RMS Spot Radius : 0.06276700
Compensator Statistics:
Change in back focus:
Minimum : -0.400000
Maximum : 0.400000
Mean : -0.000000
Standard Deviation : 0.062905

Monte Carlo Analysis:
Number of trials: 20
Initial Statistics: Normal Distribution

Trial	Criterion	Change
1	0.05052209	0.00204326
2	0.05588625	0.00740742

3	0.04754575	-0.00093308
4	0.05660730	0.00812847
5	0.05384130	0.00536247
6	0.04057629	-0.00790254
7	0.04857524	9.6407E-005
8	0.04772863	-0.00075019
9	0.05173745	0.00325862
10	0.05232406	0.00384523
11	0.04773354	-0.00074529
12	0.05330417	0.00482534
13	0.05725102	0.00877219
14	0.04749804	-0.00098079
15	0.04712328	-0.00135555
16	0.04922199	0.00074316
17	0.05489477	0.00641594
18	0.04506421	-0.00341462
19	0.04551836	-0.00296046
20	0.05126365	0.00278482

Number of traceable Monte Carlo files generated: 20
Nominal 0.04847883
Best 0.04057629 Trial 6
Worst 0.05725102 Trial 13
Mean 0.05021087
Std Dev 0.00422289

90% > 0.05624677
80% > 0.05436803
50% > 0.04987204
20% > 0.04731066
10% > 0.04529129

End of Run.

Analysis of Tolerances (iii)
File : C:\Users\ccdtest\Desktop\CurtisSchmidt_4opt_bothsurfaces.zmx
Title: Curtis Schmidt

Date : 4/20/2012
Units are Millimeters.
All changes are computed using linear differences.
Paraxial Focus compensation only.
WARNING: Boundary constraints on compensators will be ignored.
Criterion : RMS Spot Radius in Millimeters
Mode : Sensitivities
Sampling : 2
Nominal Criterion : 0.00791788
Test Wavelength : 0.6328

Sensitivity Analysis:
Worst offenders:

Type			Value	Criterion	Change
TETY	4	4	0.20000000	0.03887128	0.03095341
TETX	4	4	-0.20000000	0.03887128	0.03095341
TETX	4	4	0.20000000	0.03887128	0.03095341
TETY	4	4	-0.20000000	0.03887128	0.03095341
TETX	6	6	0.20000000	0.02835673	0.02043885
TETX	6	6	-0.20000000	0.02835673	0.02043885
TETY	6	6	-0.20000000	0.02077034	0.01285247
TETY	6	6	0.20000000	0.02077034	0.01285247
TTHI	5	6	-0.20000000	0.01499193	0.00707406
TTHI	5	6	0.20000000	0.01415989	0.00624202

Estimated Performance Changes based upon Root-Sum-Square method:
Nominal RMS Spot Radius : 0.00791788
Estimated change : 0.05065044
Estimated RMS Spot Radius : 0.05856831
Compensator Statistics:
Change in back focus:
Minimum : -0.400087
Maximum : 0.399894
Mean : -0.000003
Standard Deviation : 0.062983

Monte Carlo Analysis:
Number of trials: 20
Initial Statistics: Normal Distribution

Trial	Criterion	Change
1	0.01965771	0.01173983
2	0.01669216	0.00877428

3	0.02988825	0.02197037
4	0.04148884	0.03357096
5	0.02363295	0.01571507
6	0.02497847	0.01706059
7	0.03859751	0.03067963
8	0.03263811	0.02472023
9	0.05201186	0.04409399
10	0.01853471	0.01061683
11	0.03091441	0.02299653
12	0.02680942	0.01889155
13	0.02884148	0.02092361
14	0.01901464	0.01109677
15	0.02061781	0.01269993
16	0.02189402	0.01397615
17	0.02204743	0.01412955
18	0.03987438	0.03195650
19	0.02461376	0.01669588
20	0.01962425	0.01170637

Number of traceable Monte Carlo files generated: 20
Nominal 0.00791788
Best 0.01669216 Trial 2
Worst 0.05201186 Trial 9
Mean 0.02761861
Std Dev 0.00908140

90% > 0.04068161
80% > 0.03561781
50% > 0.02479611
20% > 0.01964098
10% > 0.01877468

End of Run.

Curtis-Schmidt Optical Elements and Ray-Tracing
Rays enter just before the aspheric corrector (at left), proceed to the primary mirror (at right), then off of the secondary through the dewar window/field flattener to the focal plane (at bottom).